CHAPTER 5. FALSEWORK STABILITY

5-1.01 Introduction

The term "stability" as it is used throughout this manual means resistance to overturning or collapse of the falsework system as a whole or that portion of the falsework system under consideration. Resistance to both overturning and collapse is provided by the falsework bracing system, which must be designed to withstand all forces resulting from application of the horizontal design load.

Note that the term "falsework bracing system" as it is used in the specifications includes bracing designed to resist overturning, bracing designed to resist collapse, and struts, ties, anchor blocks and similar features used to prevent the overturning or collapse of any falsework component. Regardless of function, however, all elements of the falsework bracing system must be designed to resist all forces generated by the horizontal design load.

It is important to recognize the distinction between "overturning" and "collapse" as these terms are used to describe the failure modes when falsework is subjected to horizontal forces. Overturning is used when the falsework bracing provides sufficient rigidity to the falsework system as a whole, or to the element of the system under consideration, so that the system or element acts as a single, rigid unit. In such cases the falsework will fail by overturning, or rotation about its base. If, however, the bracing cannot prevent distortion of the falsework when it is subjected to horizontal forces, the system will collapse internally rather than overturn. The two failure modes are shown schematically in Figure 5-1.

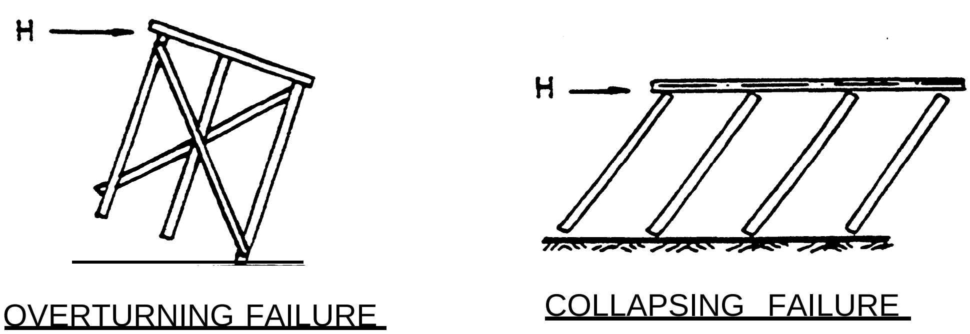

FIGURE 5-1

As a point of interest, bracing whose primary purpose is to prevent collapse is often referred to as "internal" bracing, whereas bracing whose purpose is to prevent overturning is called "external" bracing.

When investigating stability, keep in mind that the specifications do not require the falsework to carry the horizontal design load from its point of application through all members of the falsework system to the ground or other point of support. If the "falsework bracing system" will resist the overturning and collapsing forces produced by the horizontal design load, the falsework-design complies with the intent of the specifications.*

When following the provisions and procedures in this manual, stresses in falsework members produced by the application of a horizontal force need not be combined with stresses produced by vertical forces except in unusual cases where combining is necessary to ensure stability. For example, pile bents supporting falsework for structures over waterways often will be braced only above the waterline. In this type of design the bracing must be adequate to resist the horizontal design load in accordance with the general design criteria for falsework bracing systems, and the bent so braced will be considered as being rigid to the bottom of the bracing. Below the bracing, individual falsework piles will be subject to bending; consequently, horizontal as well as vertical forces must be considered and the resulting stresses combined to determine the actual stress.

Similar situations in which bending should be considered in the analysis will from time to time occur. The engineer will be expected to recognize all such situations and to combine stresses whenever this procedure is necessary to ensure the stability of the falsework system as a whole. (See Section 5-1.08, Combining Stresses, for additional information.)

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* The rationale for the specification concept is the belief that a failure due to the action of horizontal forces will occur as a consequence of the overturning or toppling of a falsework member, or the internal collapse of a braced element of the system. Failure is not expected to occur as a consequence of one falsework member sliding across another. This is not to say that such a sliding failure could not occur under any combination of forces however unique, but the possibility is so remote it may be neglected for falsework design.

5-1.02 Internal Stability

Some falsework systems have inherent stability by reason of thenature of the materials used in their construction. For example, timber falsework bents have a degree of internal resistance to collapse, particularly where large, heavy posts are used. This "internal stability" is due to restraint at the top and bottom of the post, which, in turn, produces a resisting moment.

Since the amount of internal resistance actually developed under a given loading condition is a very intangible factor, it is Division of Structures policy to neglect the inherent ability of a falsework frame to resist collapsing forces in all cases where the height of the falsework post exceeds three times the post width. When post height exceeds the limiting ratio, resistance to overturning and/or collapse must be provided by diagonal bracing, or by blocking, ties or other means approved by the engineer.

5-l.03 Diagonal Bracing

In conventional falsework systems, the individual posts making up the falsework bent are stabilized against collapse by diagonal cross-bracing. The diagonal braces are installed across two or more vertical posts and securely nailed or bolted in place to make a single, rigid unit capable of resisting the collapsing forces produced by horizontal loads.

Because of the indeterminate nature of a diagonally-braced falsework bent, investigation of bracing adequacy using conventional methods of analysis is a difficult and time-consuming process. Furthermore, rigorous studies of the behavior of braced falsework bents have revealed that the actual load imposed on the compression members, under certain loading conditions, may be as much as two times greater than would be indicated by a conventional analysis.

As a horizontal load is applied to a diagonally-braced timber frame, the tension and compression members will each contribute to the resisting capacity until the design capacity of the compression members is reached. As additional load is applied, the overstressed compression members may yield or buckle, and therefore they may be incapable (theoretically) of contributing to the ultimate strength of the frame. In view of this reality and to ensure the compatibility of results obtained by our procedure with results obtained by a rigorous frame analysis, it is Division of Structures policy to limit the contribution of the compression members, and the compression member connections, to one-half of their theoretical contribution when calculating the resisting capacity of the bracing system.

In consideration of the foregoing, the Division of Structures has developed a review procedure which simplifies the analysis and at the same time minimizes the risk of detrimental over-stressing of the compression members. This simplified procedure, called the "resisting-capacity" method of analysis, assumes that the collapsing force produced by the horizontal design. load will be resisted by the sum of the horizontal components of the allowable load-carrying capacities of the diagonals. To ensure stability, the sum of the horizontal components (i.e., the "resisting capacity" of the diagonal braces) must be numerically equal to or larger than the collapsing force.

When compression members have intermediate fasteners to reduce the unsupported length for design, Division policy requires the fasteners to be capable of resisting a force equal to five percent of the theoretical design capacity of the member, but not less than 250 pounds, applied at right angles to the member.

To ensure uniformity, Division of Structures policy requires the adequacy of diagonal bracing to be checked by the "resisting-capacity" method. The procedure depends on the number of vertical stories, or tiers, of bracing used in the bent, as discussed in the following two sections.

5-1.03A Analysis of Single-Tier Framed Bents

For single-tier bracing, the resisting capacity of the diagonal bracing system is calculated as follows, regardless of the type of fastener (nails, bolts or lag screws) used in the connection:

1. Determine the strength of the connection between brace and post. The strength value will be the same for both tension and compression members. (For this calculation, follow the procedure in Section 4-3, Timber Fasteners, for the type of fastener used.)

2. Determine the strength of the diagonal braces in tension.

3. Compare the two strength values. The smaller of these two values is the strength of the tension members.

4. Calculate the horizontal component of the strength value found in step 3. The horizontal component is the resisting capacity of the tension members.

5. Determine the strength of the diagonal braces in compression, as limited by the L/d ratio.

6. Compare the strength of the connection (calculated in step 1) and the strength of the braces in compression. The smaller of these two values is the theoretical strength of the compression members. One-half of the theoretical strength is the allowable strength of the compression members.

7. Calculate the horizontal component of the allowable strength (step 6) to obtain the resisting capacity of the compression members.

8. Add the resisting capacity of all tension members and all compression members to obtain the total resisting capacity of the diagonal bracing system.

To check bracing adequacy, compare the total resisting capacity of the diagonal bracing system, determined as provided above, and the collapsing force applied to the falsework bent.

For the comparison, the collapsing force is assumed as numerically equal to the horizontal design load acting on the bent. The collapsing force is further assumed as acting in the same plane as the horizontal forces making up the resisting capacity of the bracing system, but in the opposite direction. The resisting capacity of the bracing system must equal or exceed the collapsing force applied in either direction; otherwise the bracing is not adequate.

The "resisting-capacity" method of analysis is illustrated in example problems in the appendix.

<u>5-1.03B Analysis of Multi-Tiered Frame Bents</u>

When the diagonal bracing system consists of more than a single tier, the collapsing resistance of the frame may be limited by the resisting capacity of any individual tier of bracing within the frame. Consequently, the resisting capacity of the bracing in each tier must be evaluated independently of the other tiers to ensure that each independently-braced element of the bent (i.e., each tier) can withstand the collapsing force applied to that element.

The resisting-capacity concept as a means of checking the adequacy of diagonal bracing has been verified by subjective analysis of mathematical models of typical and atypical falsework configurations. These analytical studies reveal that a horizontal brace between the tiers in a multi-tiered frame makes only a marginal contribution to the total resisting strength of the frame, and under some loading conditions may actually decrease (although only slightly) the effectiveness of the compression members as compared to similar frames in which no horizontal braces are used. Since horizontal braces appear to be redundant members of the system, their effect on frame capacity may be neglected when checking diagonal bracing by the resisting-capacity method in all cases where the diagonals are capable of resisting compression. (Note, however, that a horizontal brace will be required between tiers in a multi-tiered frame in those cases where the diagonal braces can carry tension forces only.)

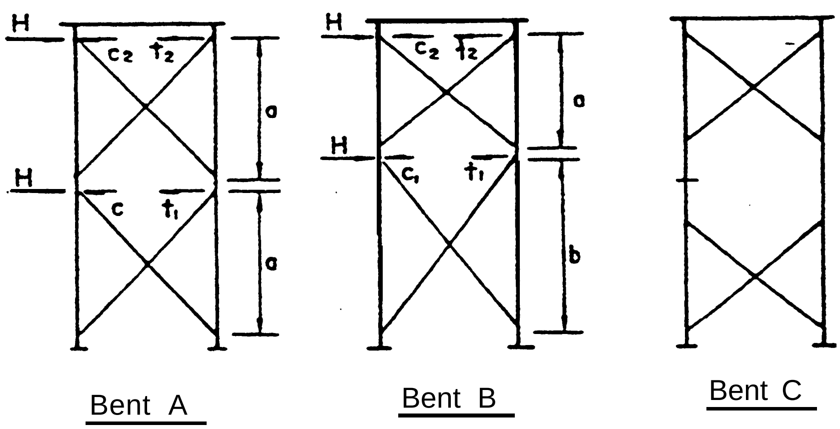


FIGURE 5-2

To understand the analysis, consider the diagonally-braced falsework bents shown schematically in Figure 5-2. Evaluating the adequacy of the bracing in Bent A, where the bracing system is the same in each tier, is simplified by symmetry. The procedure is as follows:

1. Calculate the resisting capacity of the diagonal bracing in either tier. (The values are the same for both tiers.) Follow the procedure discussed in Section 5-l.O3A, Analysis of Single-Tier Framed Bents.

2. Compare the total resisting capacity calculated in step 1 and the collapsing force produced by the horizontal design load. If the resisting capacity

equals or exceeds the collapsing force, the bracing in that tier is adequate, and therefore the bent bracing system is adequate as well.

The procedure for evaluating bracing adequacy when the bracing system is the same in each tier, as described herein for a two-tiered bent, will also apply to bents with three, or more, identical tiers of bracing.

When the tiers are of different heights or are otherwise dissimilar, the collapsing resistance provided by the bracing in me tier may not be the same as the collapsing resistance provided by bracing in other tiers. As previously noted, the resisting capacity of the bracing in each tier must be evaluated independently of the bracing in the other tiers.

Falsework Bent B in Figure 5-2 shows a-frame with unequal tier heights. The resisting capacity of the frame is determined as follows:

1. Calculate the resisting capacity of the bracing in Tier 2, following the procedure in Section 5-1.03A, Analysis of Single-Tier Framed Bents.

2. Compare resisting capacity and collapsing force. For this comparison, the collapsing force (i.e., the horizontal design load) is assumed as acting in a plane through the upper connections in the Tier 2 bracing, as shown in Figure 5-2. The resisting capacity of the bracing in Tier 2 must equal or exceed the collapsing force.

3. Repeat steps 1 and 2 for Tier 1.

If the resisting capacity of the diagonal bracing in each tier will withstand the collapsing force applied to that tier, the diagonal bracing system is adequate. If, however, the resisting capacity of either tier is less than the collapsing force, the bracing system is not adequate; hence the falsework design nay not be approved. (Note that excess resisting capacity in one tier may not be used to compensate for a deficiency in the capacity of any other tier.)

If the tiers of diagonal bracing are closely-spaced vertically, as is the case in Bents A and B in Figure 5-2, the effect of bending in the posts between the connections is small and may be neglected when investigating post capacity. If the tiers are separated, however, as are the tiers in Bent C, then bending may be an important factor.

To ensure uniformity, the effect of bending on post capacity will be investigated in accordance with the following policy:

1. If neither the vertical distance between tiers of bracing nor the unbraced post length extending above or below the tiers exceeds four times the post width, bending may be neglected.

2. If either the vertical distance between tiers of bracing or the unbraced post length extending above or below the tiers is greater than four times the post width, bending in the post including secondary effects due to horizontal deflection (i.e., the $P\Delta$ effect) must be considered. The analysis should follow the procedure for evaluating the adequacy of timber pile bents (see Chapter 7) except that the posts will be considered as pinned at both the top and bottom.

External cable bracing-will not prevent horizontal deflection at the top of a multi-tiered frame, even though the cable system is properly designed to resist overturning. Therefore, cables designed to prevent overturning may not be used to reduce the horizontal design load when investigating member adequacy under combined vertical and horizontal forces.

When bending is a factor for investigation, as discussed in subparagraph (2) above, the contractor's design calculations must consider the effect of horizontal deflection on member stresses, including the $P\Delta$ effect.

5-1.03C Steel Bracing

The resisting-capacity method of analysis, as discussed in the preceding sections, is also applicable when steel bracing is used with either steel or timber posts.

When bolted connections are used, the bolt values may be. taken from the AISC Manual of Steel Construction. The calculated bearing stress on the projected area of the bolt may not exceed 1.5 Fu where Fu is the specified minimum tensile strength of the steel. For A36 grade steel, Fu is 58 ksi.

The strength of welded connections may be approximated by assuming a value of 1000 pounds per inch for each 1/8-inch of fillet weld. While this value may appear conservative for permanent work where welding is performed under controlled conditions, it is a realistic value for the techniques and procedures commonly used when welding falsework components.

If a higher weld value is required by the design, welding procedures must conform to the quality standards normally associated with permanent construction. See Section 9-1.05, field Welding.

Structural steel elements (angles, channels, bars, etc.) are used occasionally as diagonal cross-bracing in timber bents. In such cases the NDS bolt design values for parallel-to-grain loading may be increased 75 percent, as provided in NDS Paragraph 8.5.6.3. No increase is allowed for perpendicular-to-grain loading, however.

5-1.04 Longitudinal Stability

To ensure longitudinal stability, it is necessary to provide a system of restraint that will prevent the falsework bents from overturning when the horizontal design load is applied in the longitudinal direction. This can be accomplished by diagonal bracing between pairs of adjacent bents, or by transferring the horizontal load from one falsework span to the next falsework span ahead without allowing any horizontal force to reach the bent between the two spans.

Consider, for example, the falsework system shown schematically in Figure 5-3. Longitudinal forces generated by the horizontal design load are carried in either direction across unbraced bents D and E to the point of longitudinal restraint at bents C and F. The falsework system is stabilized by diagonally-braced bents B-C and F-G, which are each designed to resist one-half of the total horizontal load acting on the system.

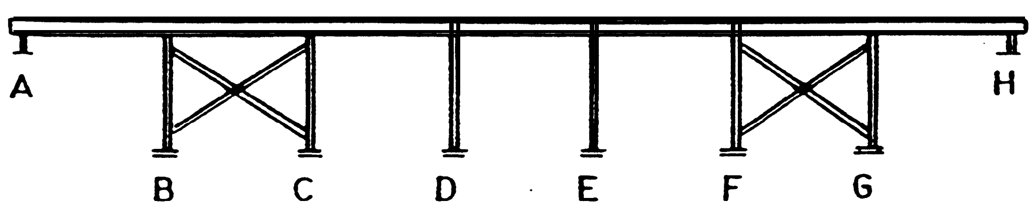


FIGURE 5-3

The adequacy of longitudinal cross-bracing used to stabilize adjacent bents will be determined in accordance with the procedure discussed in Section 5-1.03, Diagonal Bracing.

The method by which the horizontal design load is carried across an unbraced bent should be carefully scrutinized to ensure that horizontal forces cannot reach the bent under any loading condition. Many designs will take advantage of frictional resistance between stringer and cap to transfer at least a part of the total longitudinal force acting at the bent. When investigating the load transfer capability of such designs with the falsework in an unloaded condition, keep in mind that friction will not be developed until a vertical load is applied, Therefore, in the unloaded condition do not allow more frictional resistance than will be developed by the dead load of the falsework members plus an allowance for the weight of forms and reinforcing steel.

If frictional resistance alone is not sufficient to withstand the horizontal design load, some positive means of restraint must be provided to carry that portion of the total load in excess of the maximum allowable frictional resistance. The term "positive means of restraint" includes blocking, bracing, dowels, clips, cables and similar mechanical connecting devices which are capable of transferring horizontal forces in the absence of a vertical load, but it does not include "C" clamps when such devices are proposed for use as a means of increasing the friction between stringer and cap or other adjacent falsework members.

Devices used to transfer horizontal forces across an unbraced bent must be spaced far enough apart transversely so as to prevent eccentric loading on the restraining member. In general, this will require at least two points of mechanical transfer for each independent element of the falsework system. One-point transfer may be acceptable under unusual circumstances such as a case where the force to be transferred is small when compared to the total horizontal load, or where each independent element is relatively narrow. This is a matter of engineering judgment. In case of doubt, two points of load transfer should be required.

5-1.05 Overturning

If the falsework system, or the element of the system under consideration, is adequately braced to prevent collapse, the system or element may nevertheless fail by overturning, or rotation about its base, when the horizontal design load is applied. Overturning failure will occur unless the falsework is inherently stable against overturning by reason of its configuration, or is externally braced to prevent overturning.

If stability analysis, it is assumed that the horizontal design load produces a moment that acts to overturn the falsework system or element of the system under consideration. For descriptive purposes, this moment is called the "overturning" moment.

When calculating overturning moments, the moment arm will be measured from a plane at the top of the falsework member that is set on the ground, and the horizonal design load will be applied to the falsework in accordance with the following:

Actual loads (such as those due to construction equipment or to the concrete placing sequence) will be considered as acting at the point of application to the falsework.

Wind loads will be considered as acting at the centroid of the wind impact area for each height zone. When wind loads govern the design, however, the horizontal design load (to be used in calculating the overturning moment) is applied in a plane at the top of the falsework post or shoring. See Section 3-1.05, Wind Loads.

All other horizontal loads, including the minimum load when the minimum load governs, will be assumed as acting in a plane at the top of the falsework posts or shoring.

When calculating the moment acting on other elements of the falsework where stability is a factor for consideration, such as a pony bent system, the moment arm will be measured from the base of that particular falsework element. Actual loads and wind loads will be applied in accordance with the criteria in the preceding paragraphs. All other horizontal loads will be assumed as acting in a plane at the top of the element of the falsework system under consideration.

5-1.05A Calculation of Resisting Moments

When a horizontal load is applied to a falsework frame or tower, the overturning moment thus produced will be resisted up to a point by a resisting or righting moment generated by the weight of the falsework and the total supported dead load. If the resisting moment is greater than the overturning moment, the falsework is stable against overturning and no external bracing will be required. If the resisting moment is less than the overturning moment, the difference must be resisted by bracing, cable guys or other means of external support .*

* For falsework analysis it is not necessary to provide a factor of safety against overturning. In accordance with Division of Structures policy, if. a falsework frame or tower is theoretically stable (no uplift in any post or tower leg) external bracing is not required.

When calculating resisting moments for falsework in the "unloaded" condition, the total supported dead load will include the weight of falsework beams, forms and reinforcing steel, but not concrete. In the "loaded" condition, the weight of the concrete actually in place will be included as well.

To facilitate analysis, the weight of forms and reinforcing steel in pounds per square foot of bridge soffit may be estimated. Use a factor of 1.5d for prestressed structures and 2.33d for conventionally reinforced structures, where "d" is the superstructure depth in feet.

5-1.05B Effect of Overturning on Post Loads

When external bracing is not required to resist overturning, do not overlook the effect of the overturning moment on post loads when the falsework is fully loaded, Consider the bent in Figure 5-4.

In the loaded condition the theoretical post load (dead load plus live load) of 50 kips will be increased or decreased by the post reaction created by the overturning moment, or the vertical component of the resisting couple acting through the post. In the bent shown, the reaction is 4 kips and the post design load is 54 kips.

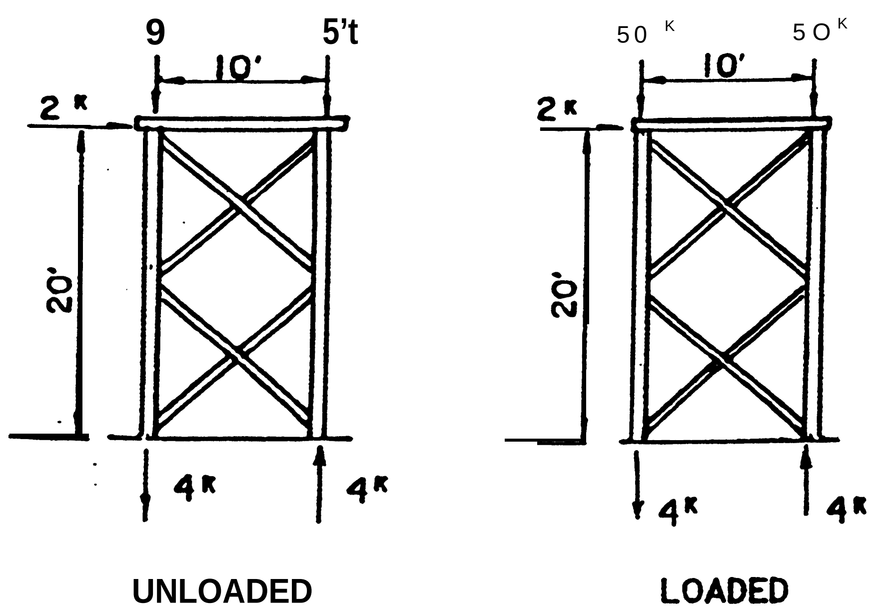


FIGURE 5-4

In a stable bent with more than two falsework posts, the post reactions are proportional to their distances from the center of rotation, and may be obtained by algebraic summation.

5-1.06 Pony Bent Systems

The stability of pony bent systems should be given special consideration. Pony bents should be independently braced, and the bracing must be capable of resisting the overturning moment produced by the horizontal design load acting at the top of the pony bent.

Pony bents are usually erected on and supported by a platform constructed at the top of the primary load-carrying members.
The platform functions as a horizontal diaphragm, and thus stabilizes the entire falsework system.

If a stabilizing platform is not incorporated into the falsework design, the individual bents must be braced or tied together in some manner to prevent lateral displacement at the bottom of the pony bent system.

5-1.07 Multiple & Built up Cap Systems

Multiple cap systems are inherently less stable than single cap systems. Similarly, cap systems that are poorly constructed by utilizing an excessive amount of built-up material between the supporting foundation and cap beam are more vulnerable to stability problems.

When investigating the stability of a multiple cap system, it is important to remember that the stability of the system will decrease as the distance between the supporting members and the top of the cap/sill beam increases. Cap and sill beam assemblies (as defined below) should adhere to a maximum height to width ratio of 2:1 unless the falsework designer determines that a more conservative approach is needed. In addition, multiple layers of supporting material must be equal or greater in width than the previous layer, hence forcing a pyramid shape. These requirements are illustrated in the following Figures 5-5,5-6 and 5-7.

The following cap/sill beam definitions shall be used for purposes of checking the **2:1 ratio.**

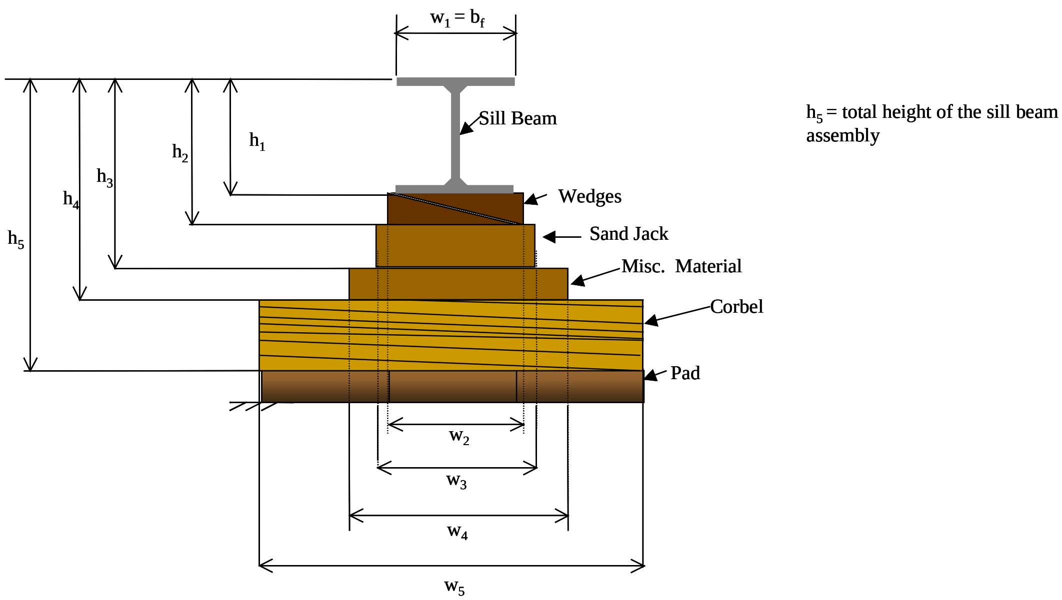
> In the overturning direction **perpendicular to the centerline** of the falsework bent, a sill beam assembly shall include all material from the **top**

flange of the sill beam to the top of the pad (See Figures 5-5 and 5-6). A cap beam assembly shall include all the material from the **top** flange of the cap beam to the top of the post.

In the overturning direction **parallel to the centerline** of the falsework bent, a sill beam assembly shall include all material from the **bottom** flange of the sill beam to the top of the pad (See Figure 5-7). A cap beam assembly shall include all the material from the **bottom** flange of the cap beam to the top of the supporting member (e.g. post).

The 2:1 height to width criteria shall be strictly enforced during both falsework plan review and construction phases. Often multiple capping or excessive stacking of material is done to correct grade errors discovered during falsework construction. This is an unacceptable construction practice and shall not be allowed.

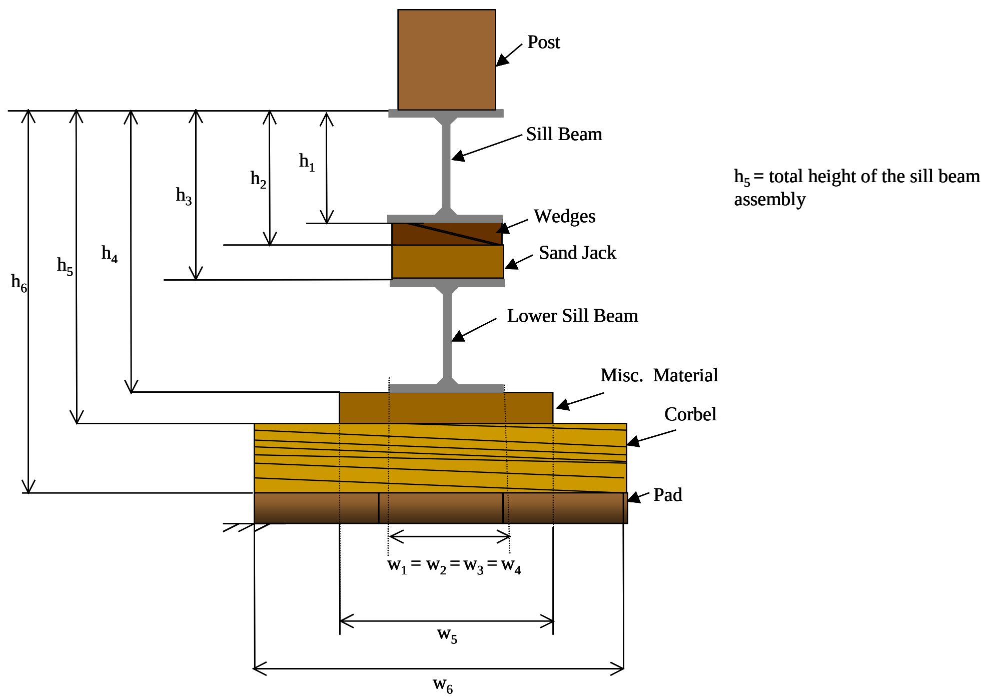
On occasion a situation may arise where the falsework designer chooses to engineer a cap/sill assembly that does not meet the 2:1 height to width criteria. In general cap/sill assemblies that do not meet the 2:1 ratio should be strongly discouraged and alternatives should be explored. However, the 2:1 criteria may be exceeded if the falsework cap/sill assembly is externally stabilized. The external stabilizing support system must be designed to withstand the greater of the horizontal wind or construction load or a minimum 2% of the falsework dead load force (similar to the longitudinal stability analysis) applied to the top of the upper most cap/sill beam. In addition, the stabilizing support system must be designed to accommodate both grading adjustments and bent settlement without inducing additional horizontal loads into the cap system.



Stability Requirement (Overturning direction perpendicular to the falsework bent)

$$h_i \leq 2w_i \quad (w_i \geq w_{(i-1)} \geq b_f)$$

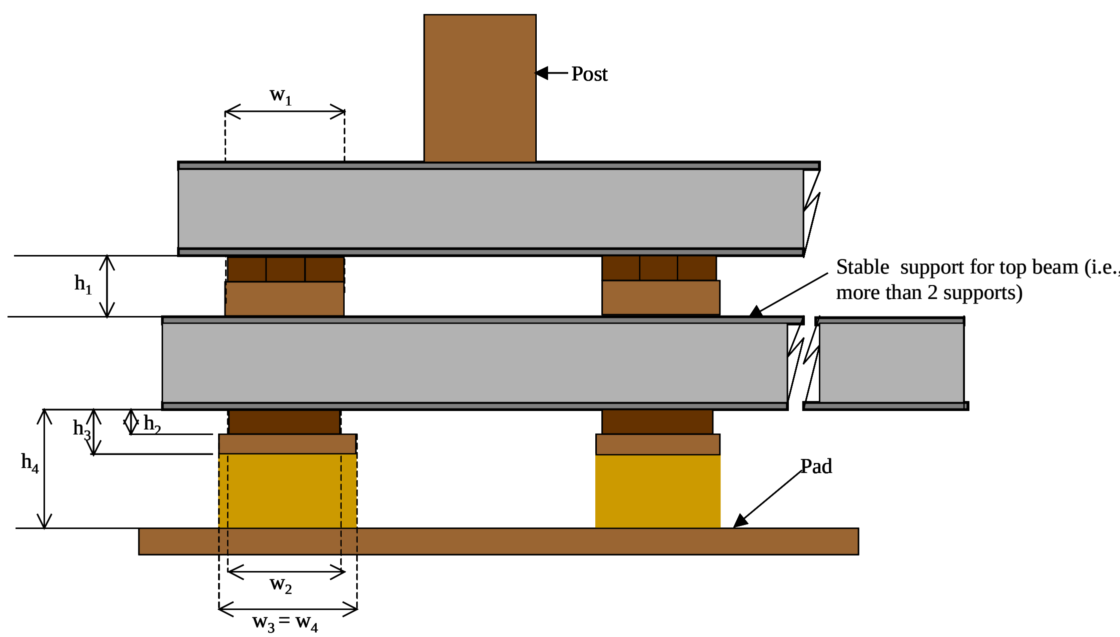
Figure 5-5



Stability Requirement (Overturning direction perpendicular to the falsework bent)

$$h_i \leq 2w_i \quad (w_i \geq w_{(i-1)} \geq b_f)$$

Figure 5-6



Stability Requirement (Overturning direction parallel to the falsework bent)

$$h_i \leq 2w_i$$

Figure 5-7

5 – 1.08 Combining Stresses

As noted elsewhere in this manual, stresses produced by the simultaneous application of horizontal and vertical forces need be combined only in those situations where bending must be considered to prevent overstressing of an axially-loaded member of the falsework system. Examples of such situations will include pile bents over water where the bracing extends only to the water surface and multi-tiered frame bents where the bracing system, although adequate to resist the collapsing force, does not fully support the vertical members in the bent and/or cannot prevent side sway.

The ability of a falsework member to resist the combined effect of bending and axial compression is evaluated by the combined stress expression. The combined *stress* expression, or interaction formula as it is sometimes called, establishes a limiting relationship between bending and compressive stresses such that the sum of the actual/allowable ratios of the two stresses may not exceed 1. In formula form the combined stress expression is:

$$f_b/F_b + f_c/F_c \leq 1$$

Where f_b and f_c are the calculated bending and compressive stresses, respectively, and F_b and F_c are the allowable values for bending and axial compression as listed in the specifications.

The combined stress expression may be used to determine the adequacy of falsework members to resist bending and axial compression in all cases except driven timber piles. Timber piles should be evaluated in accordance with the procedures discussed in Chapter 7.